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AN ASTEROSEISMOLOGY EXPLORER

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Abstract. In response to a NASA opportunity, a proposal has been made to study the concept of an Asteroseismology Explorer (ASE). The goal of the ASE would be to measure solar-like oscillations on many (perhaps hundreds) of stars during a 1-year mission, including many members of open clusters. We describe this proposal's observational goals, a straw-man technical approach, and likely scientific rewards.

Background

Solar p-mode oscillations have become a fruitful source of information about solar structure (Christensen-Dalsgaard *et al.* 1985). Motivated by the solar example, many workers have made recent attempts to detect solar-like oscillations on other stars. It seems likely that these attempts will succeed in the near future, but it is obvious that the amounts of large-telescope time required to make even a partial survey of nearby solar-like stars will be prohibitive. In view of this situation and stimulated by a NASA opportunity, a small group (including the authors, H.S. Hudson, J.W. Harvey, R.W. Noyes, J. Christensen-Dalsgaard, P. Demarque and J.T. McGraw) has considered whether such a survey might be conducted from space, and what its scientific rewards would be. The result of our efforts was a proposal to study the concept of an Asteroseismology Explorer (ASE). We describe here the current state of thinking about the ASE, partly to inform the community of its possibilities, and partly to solicit ideas for improvement.

Compared to familiar stellar pulsations, the solar p-modes are distinguished by their short periods (5 m), their large radial order (typically 20, for large spatial scales) and their small amplitudes (10 cm/s in velocity, or 3×10^{-6} in relative continuum intensity). Though many inferences about the solar interior rely on observation of strongly nonradial

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oscillations, there is much to learn from oscillations with angular degree l between zero and three. This range of l may be detected using light integrated over the stellar disk, and hence is accessible even on distant stars. A particularly striking example of this ability (and the paradigm for the ASE) is the time series of solar irradiance obtained by the ACRIM instrument on the SMM satellite (Willson 1979). This device is a radiometer, intended to measure changes in the solar constant with absolute precision of about 10^{-3} , and with random noise for a single 128 s integration of about 3×10^{-5} . In spite of this large noise level, power spectra of time series taken with the ACRIM show the individual solar p-modes clearly for $l = 0-2$, and give one of the best current estimates of their frequencies (Woodard and Hudson 1983).

What can one learn from these modes? The frequency spectrum for low- l p-modes consists of pairs of modes with $l = 0, 2$ and $l = 1, 3$. The modes in each pair have nearly identical frequencies, and the pairs are separated by $\nu_0/2$, where ν_0 is a parameter determined principally by the star's mean density. For the Sun, ν_0 is about 130 μHz ; ν_0 decreases as the stellar radius increases. Conditions in the stellar core determine the splitting between modes within each pair. The splitting between modes with $l = 0$ and $l = 2$ is typically 8-12 μHz in cool dwarfs; it is expected to decrease as the star evolves (Christensen-Dalsgaard 1984, Ulrich 1986). Observing a value for this splitting would require 2-5 days of observation, and would allow an estimate of the star's evolutionary state. In addition to structural information, one can hope to observe the rotational splitting of modes with the same radial order and angular degree, but different azimuthal order. This splitting depends on the angular rotation speed of the star, averaged over most of its interior. Combined with photometric or spectroscopic estimates of the surface rotation rate, one might thus learn whether stellar envelopes spin down first, leaving a rapidly rotating core. Observing the amplitudes of p-mode oscillations for a range of stellar masses, ages, and activity levels would certainly cast light on the mechanisms responsible for exciting the modes. Finally, we anticipate that a broad survey of many stars may reveal relationships that would not appear in a detailed study of any single one, especially if many of the stars studied are cluster members, and therefore approximately coeval and of similar initial composition.

Based on these considerations, the principal goal of the ASE is to observe a large number (perhaps a few hundred) of roughly solar-like stars, with enough precision and temporal coverage to detect and classify their p-mode oscillations. A large fraction of these stars should lie in clusters, or should be members of visual binary systems, both to maximize the number of target stars in each field of view, and for the astrophysical reasons just mentioned. However, because of the limited age range of nearby clusters, it will certainly be necessary to spend much (perhaps most) of the observing time on selected field stars.

II. Technical Approach

Mainly for reasons of technical feasibility, we chose to detect oscillations by observing their associated photometric variations. The anticipated mode relative intensity amplitudes are a few times 10^{-6} , (i.e., micromagnitudes), and these must be detected within the typical mode lifetime of 10^6 s. It is very important to note that one need not do *absolute*

photometry at the micromagnitude level. Rather, one can (and probably must!) do photometry that is *relative* in both space and time: one requires stability only over a small fraction of the field of view, for times somewhat longer than the oscillation period. Since we wish to observe solar-like stars in nearby clusters, we must be able to reach micromagnitude precision for stars as faint as about $m_v = 10$. Finally, in order to make simultaneous observations on as many stars within a cluster as possible, we would like a field of view at least 2° in diameter.

These observational requirements prescribe many of the system parameters. To obtain micromagnitude precision in 10^6 s, one must detect at least 10^6 photon/s. To do this for a 10th magnitude star using a broadband telescope with reasonable transmission requires an aperture of about 1 m. Covering a 2° field of view with the largest "available" CCD detector (the Tektronix 2048 x 2048) requires a focal length of about 1 m. Finally, to obtain good photometry on bright objects one must avoid saturating any of the CCD pixels, which implies that the images must be large (to cover many pixels), and the detector must be read out at the highest feasible rate.

These requirements lead to a design incorporating a 1 m aperture, $f/1.2$ Schmidt telescope, with a field flattener and a single 2048 x 2048 pixel CCD detector at the prime focus. This arrangement covers a field 2.56° square, with a resolution of 4.5 arcsec/pixel. By defocusing the stellar images to about 50 arcsec diameter, binning multiple pixels on-chip, and reading the detector at 1 MHz, one can construct a system that will detect 10^6 photons/s from stars with $m_v = 10.1$, and begins to saturate at $m_v = 8.0$. With exposures just 100 s in length, such a system could detect millimagnitude changes on stars with $m_v = 15$. Making a detector system to these specifications will be a challenge, particularly because of the large dynamic range encountered and the high readout rates required. Simulations based on our experience with current CCD systems suggest that we can meet this challenge, however.

The baseline orbit for this telescope is one with 57° inclination and 500 km altitude. Most nearby galactic clusters would fall into the continuous viewing zone of this orbit at one time or another, with periods of 75% visibility lasting for 15 to 20 days. The once-per-orbit data gaps that appear during times of partial target visibility would be obnoxious, but tolerable. The 74-day precession period of the orbit would allow several opportunities to observe each target field during a 1-year mission. The mode of operation would be to observe each chosen field continuously for ten days or more, averaging images over roughly 60 s intervals before transmitting them to the ground. We believe that all of the information in each image should be preserved in the transmission process. Since the images involved are precisely as unchanging as the heavens, efficient data compression techniques are possible; we estimate that a downlink rate of 4×10^4 bits/s should suffice. Once the data reach the ground, it will be possible (and desirable) to construct a photometric time series for each identifiable object in the field of view. For most fields, the limiting magnitude for effective photometry will be determined by confusion with faint background stars, rather than instrumental or photon noise.

III. Discussion

The system just described would be able to detect solar-like oscillations on GV stars as far away as the Pleiades; half a dozen other clusters and several hundred late-type dwarf field stars lie within that distance — enough for an informative first survey. It will be particularly productive to study stars with well-established physical parameters, ages, and activity indices. From this point of view the Hyades cluster is a very important target, as are the α Perseus group and the Pleiades. Obtaining adequate ancillary information about possible field star targets is likely to require a substantial ground-based effort. In addition to these candidates for asteroseismology, one should expect to see many of the more familiar pulsating stars: δ Scuti variables, Cepheids, rapidly oscillating Ap stars, flare stars and oscillating white dwarfs. Detection of low-amplitude variables of the more traditional types would assist in identifying the edges of instability strips and understanding pulsation mechanisms. One could also use the data set from the ASE to address problems unrelated to oscillations. For example, power spectra of the photometric changes due to stellar convection are likely to be observable (ACRIM observes them on the Sun). The way in which these spectra depend on stellar mass, age, and metallicity could improve our knowledge of the convection process in general. Low mass stellar companions, even those of planetary size, would make detectable light variations if they were to transit a stellar disk; whether or not such events are seen, one can use the observations to set statistical limits on the number of such companions.

What important questions remain to be answered about the ASE, i.e., what issues should be addressed by a NASA-funded study? The most vital is to verify that one can do micromagnitude time-series photometry using current CCD technology; this will require careful laboratory work. It will also be necessary to perform a number of tradeoff studies to determine the best choice of parameters for the instrument, the optimum observing sequence, and suitable means for reducing and accessing the large amounts of data that will be produced. To make these tradeoffs it will be necessary to know exactly what are the scientific priorities, what observations are needed to meet these goals, and how these requirements affect the instrument design and mission plan. We hope that other stellar astronomers will help us to answer these questions.

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